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Growth and Nutrient Concentrations of Common Bean, Lowland Rice, Corn, Soybean, and Wheat at Different Soil pH on an Inceptisol

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ABSTRACT

Soil pH is an important soil chemical property of acid soils that profoundly affects the growth and nutrient uptake by crops. Five greenhouse experiments were conducted to evaluate responses of common bean (*Phaseolus vulgaris* L.), lowland rice (*Oryza sativa* L.), corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), and wheat (*Triticum aestivum* L.) to mean soil pH values of 4.9, 5.9, 6.4, 6.7, and 7 on an Inceptisol. Relative dry matter yield (DMY) of shoots of all the crops tested was significantly affected by soil pH. Based on the quadratic response optimum pH for maximum relative Dry matter yield of wheat was 6.3, for soybean 5.6, for corn 5.4, for common bean 6 and for rice 4.9. This shows that crops responded differently to soil acidity. Among the crops tested, rice was the most tolerant and wheat was the most intolerant to soil acidity. On an average concentration of calcium (Ca) and potassium (K) in the plant shoots increased quadratically with increased soil pH except K concentration in the

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shoots of corn and soybean decreased. Magnesium (Mg) concentrations in the shoots of common bean and wheat decreased with increasing soil pH but in lowland rice, corn, and soybean increased quadratically with increasing soil pH. Phosphorus (P) concentrations in the shoots of common bean, wheat, and corn was increased but in lowland rice and soybean decreased with increasing soil pH. With few exceptions, most of the micronutrients concentrations decreased with increasing soil pH.

INTRODUCTION

For crop plants, nutrient availability is affected by soil pH, thus affecting plant growth (Adams, 1984; Fageria et al., 1997). Plant growth on an acid soil may vary with soil pH, clay mineral types and amounts, the type and amount of organic matter, levels of salts, and particularly, with plant species or genotypes (Foy, 1984). Acid soil toxicity is not caused by a single factor but a complex of factors that includes toxicities of Al^{3+}, Mn^{2+}, and H^{+}, and deficiencies of nitrogen (N), P, K, Ca, Mg and micronutrients (Baligar and Fageria, 1997). In acid soils of Brazil, deficiencies of zinc (Zn), boron (B), and copper (Cu) have been reported (Fageria, 1984; Fageria et al., 1996).

Soil pH is often highly changeable property because of the dynamic nature of various soil processes and the interactions of these processes with plants and microorganisms (Adams, 1984). The critical soil pH value, defined as the maximum pH at which liming increases crop yield, varies among soil types, crop species, and cultivars of the same species (Adams, 1984; Fageria, et al., 1997; Rhoads and Manning, 1989). Some yield-limiting factors, such as aluminum (Al) and manganese (Mn) toxicities and Ca and Mg deficiencies, are corrected by liming; but soil pH is highly correlated with one or more of these yield-limiting factors (Adams, 1984). Identifying the critical pH for a particular crop is necessary for advising growers on the need for liming (Adams 1984). In some cases, liming to a pH of 6.5 to 7.0 can be detrimental to crop production (Kamprath, 1970; Liebhardt, 1979). Reeve and Sumner (1970) observed increased growth response for corn up to the point of eliminating exchangeable Al with several Oxisols, after which a significant yield reduction occurred. Martini et al. (1974) obtained optimum yield of soybean when liming adjusted pH of Oxisols from 5.2 to 5.7. The optimum pH range across the soil for corn has been reported to varied from 6.2 to 6.8 in Mollisols to 5.0 to 5.6 in Oxisols (Farina et al., 1980).

Little information is available on the effects of pH on crop production in Inceptisols. The objective of this study was to determine the responses of lowland rice, wheat, corn, common bean, and soybean to soil pH in a controlled soil environment, where the whole roots were subjected to a uniform acid soil (as opposed to the field situation where there is only an acid surface) throughout the growing season. Effects of soil pH on uptake of nutrients by these crop species were also evaluated.

MATERIALS AND METHODS

Five glasshouse experiments were conducted simultaneously at the National Rice and Bean Research Center of EMBRAPA, Santo Antonio de Goias-Goias, Brazil. The soil used in all five experiments was an Inceptisol (clay-loamy, isothermic, Typic Haplaquepts). Before inducing pH levels, the soil used in the five experiments had the following chemical properties: pH 5.2, Ca 3.6 $cmol_c\ kg^{-1}$, Mg 2.9 $cmol_c\ kg^{-1}$, Al 0.2 cmolc kg^{-1}, P 3 mg kg^{-1}, K 137 mg kg^{-1}, Cu 5.1 mg kg^{-1}, Zn 2.8 mg kg^{-1}, Fe 220 mg kg^{-1}, Mn 74 mg kg^{-1}, and organic matter content of 14 g kg^{-1}. Soil pH was determined in a 1:2.5 soil-water ratio. Phosphorus, K, and the micronutrients were extracted by the Mehlich 1 extracting solution (0.05 *M* HCl+0.0125 H_2SO_4). Phosphorus was determined colorimetrically, K by flame photometry, and micronutrients by atomic absorption spectrophotometry. Calcium, Mg, and Al were extracted with 1 *M* KCl. Aluminum was determined by titration with NaOH, and Ca and Mg by titration with EDTA. Organic matter was determined by the Walkley-Black method in which oxidizable matter in a soil sample is oxidized by 1 N $K_2Cr_2O_7$ and H_2SO_4 solution and titrated with standard $FeSO_4$ solution. Detailed descriptions of all the soil analysis methods are given in the Soil Analysis Manual of EMBRAPA (1997).

Five rates of liming materials were applied to create different levels of soil pH. These liming rates were 0, 30, 70, 100, and 150 g per pot. Each pot contained 5 kg of soil. Each pot also received 10 g of fertilizer mixture of 4-30-16 (N, P_2O_5, K_2O) and was incubated for 44 days. The lime used had CaO 4.93%, MgO 2.8%, $CaCO_3$ 88%, $MgCO_3$ 5.9%, and neutralizing power of $CaCO_3$ 74%. At sowing time, soil samples were collected from each pot, and a composite sample was made for each treatment, with three replications. The pH levels created were 4.9, 5.9, 6.4, 6.7, and 7. The experiment design in all experiments was a complete block with three replications. Cultivars planted were Javae for lowland rice (*Oryza sativa* L.), Apore for common bean (*Phaseolus vulgaris* L.), Pioneer 3069 for corn (*Zea mays* L.), Estrela for soybean (*Glycine max* L. Merr.), and PF 89481 for wheat (*Triticum aestivum* L). There were three plants per pot in all five experiments. In all experiments, soil moisture was maintained approximately at field capacity except for rice, which was flooded 12 days after sowing, and approximately 2 cm of water depth was maintained.

Plants in all experiments were harvested four weeks after sowing. After harvesting, the shoots were washed with distilled water several times before drying. Plant material was dried in a forced-draft oven at about 70°C until a constant weight, and was milled. Ground material was digested with mixtures of nitric and perchloric acids (2:1) for determination of P, K, Ca, Mg, Zn, Fe, Cu, and Mn. The P concentration in the digest was determined colorimetrically. All other nutrients (except B) were determined by atomic absorption spectroscopy (Morais and Rabelo, 1986). Boron concentration in the plant tissue was determined by Gains and Mitchell (1979) method.

After harvesting plants in each experiment, soil samples were taken from each pot, and a composite sample was made for each treatment, with three replications. The soil pH values were 4.9, 5.9, 6.3, 6.6, and 6.9 at harvest, very close to values at planting. Appropriate regression models selected on the basis of probability level significance and higher R^2 values were adjusted to growth and nutrient uptake data to evaluate treatment effects.

RESULTS AND DISCUSSION

Soil Chemical Properties

Soil pH had a significant effect on extractable Ca, Mg, Al, P, Cu, Zn, Fe, and effective cation exchange capacity (ECEC) (Table 1). Extractable Ca, P, Cu, Zn, and ECEC increased with increasing soil pH in quadratic fashion. Maximum value for extractable P was obtained at a pH of about 5.7, calculated by quadratic equation (Table 1). This has special significance in managing acid soils, because P deficiency is one of the most important yield-limiting nutrients in crop production in the acid lowland soils of Brazil (Fageria et al., 1995). The availability of P in these soils is highly pH-dependent and, up to some extent, it can be improved with liming. The decrease in soil extractable P at lower and higher pH levels is related to its fixation. The main mechanism for P fixation (decreased availability) under acidic conditions appears to be the precipitation as highly insoluble Fe and Al phosphates. Phosphate availability also tends to decrease at higher soil pH (>6), because of precipitation as an insoluble Ca compound (Bohn et al., 1979).

Effective cation exchange capacity (ECEC) is an important parameter for predicting fertility behavior of agricultural soils, and in the current study this has been increased significantly ($P<0.01$) with increasing pH in a quadratic response. At low pH values, Al^{3+} is the predominant exchangeable cation on clay minerals. As the pH is raised, the Al^{3+} hydrolyzes, freeing the exchange sites for Ca^{2+}, and results in an increase in the ECEC (Thomas and Hargrove, 1984). Extractable Cu, and Zn were increased up to about pH 5.5 and than decreased in a quadratic mode with increasing soil pH. The decrease in extractable Cu and Zn, was 48 and 21%, respectively, at the highest pH value (7) compared to the lowest pH value (4.9). The concentration of extractable Fe and Al decreased linearly with increasing soil pH (Table 1). This is in agreement with the hypothesis that, in general, the availability of the micronutrients and toxic cations increases with increasing soil acidity (Bohn et al., 1979).

Plant Growth

The relative DMY of shoots of wheat, corn, lowland rice, soybean, and common bean, expressed as percentages of the maximum yields obtained at various soil pH levels, are presented in Table 2. Dry matter yield of wheat corn, soybean, and common bean were significantly increased initially in a quadratic response with

TABLE 1. Soil chemical properties under different pH levels.

pH H_2O	Ca $cmol_c\ kg^{-1}$	Mg $cmol_c\ kg^{-1}$	Al $cmol_c\ kg^{-1}$	P $mg\ kg^{-1}$	K $mg\ kg^{-1}$	Cu $mg\ kg^{-1}$	Zn $mg\ kg^{-1}$	Mn $mg\ kg^{-1}$	Fe $mg\ kg^{-1}$	ECEC $cmol_c\ kg^{-1}$
4.9	4.9	3.0	0.3	54.3	423	6.3	3.9	477	297	9.3
5.9	10.0	2.6	0.1	71.9	406	6.3	4.2	458	231	13.7
6.4	11.4	2.3	0	58.4	383	5.8	4.0	492	187	14.6
6.7	12.3	2.5	0	43.3	412	5.0	3.6	484	158	15.9
7.0	12.5	2.1	0	29.8	377	3.3	3.1	506	148	15.6
Regression										
β_0	-56.47	4.70	1.11	-795.52	668.87	-39.27	-15.46	1708.34	673.50	-44.82
β_1	18.61	-0.36	-0.17	302.42	-73.09	16.70	6.96	-433.80	-75.69	16.53
β_2	-1.25	-	-	-26.38	4.73	-1.51	0.62	37.41	-	1.12
R^2	0.95**	0.41*	0.84**	0.72**	0.14ns	0.94**	0.90**	0.07ns	0.55**	0.96**
n	15	15	15	15	15	15	15	15	15	15

*, **, ns=Significant at the 5 and 1% probability levels and not significant, respectively; n=number of measurements.

TABLE 2. Relative dry matter yield of shoots (%)of five crop species under different soil pH.

pH in water	Wheat	Corn	Lowland rice	Soybean	Common bean
4.9	53	83	70	80	49
5.9	78	91	41	94	91
6.4	87	68	38	69	59
6.7	80	69	40	55	64
7.0	76	60	38	35	56
Regression					
β_0	-507.42	-238.69	503.77	-846.19	-811.65
β_1	185.33	120.16	-140.28	336.19	298.57
β_2	-14.54	-11.08	10.56	-30.07	-25.04
R^2	0.66**	0.50*	0.47*	0.84**	0.46*
n	15	15	15	15	15

*,**Significant at the 5 and 1% probability levels, respectively; n=number of measurements.

increasing soil pH from 4.9 to 5.9. The maximum DMY of shoots of wheat was achieved at the pH 6.3, and soybean at the pH 5.6, as calculated by quadratic equations. The relative DMY of wheat was 81% at pH 6.6 as compared to 53% at pH 4.9. Similarly, the relative DMY of shoots of soybean was 91% at pH 5.6, and 80% at lowest pH value of 4.9. Maximum yield of corn and common bean were achieved at the pH of 5.4 and 6, respectively. However, at higher pH yield of corn, lowland rice, soybean, and common bean crops decreased. The DMY of shoots of rice was significantly decreased with increasing pH, showing a quadratic response ($P<0.05$), and maximum yield was achieved at the lowest pH (4.9). McLean and Brown (1984) compared data of various annual crop responses to lime in the acid soils of Midwestern United States and concluded that the average minimum pH value considered desirable for corn was 6.4, for soybean was 6.5, and for wheat was 6.3. Results of adequate pH levels obtained for corn and soybean in our study were slightly lower, whereas adequate pH level for wheat was almost similar to the reported value. McLean and Brown (1984) also reported that soybean yields drop off progressively more with decreased pH than do corn yields. Similar results were obtained in our study. This difference may be due to crops differing in their sensitivities to toxic elements, such as Al and Mn, at low pH and that legumes differ in their N_2 fixation versus pH relationship at all pH levels. Munns and Fox (1977) observed a large diversity of responses among 19 crop species, that they grew across a pH gradient of 4.7 to 7.1 on a humid tropical soil. Based on responses of DMY of shoots to soil pH, five crops tested in this study can be grouped in the order of rice>corn>soybean>common bean>wheat to soil acidity. Tolerance of rice to soil acidity, and intolerance of soybean, common bean, and wheat to soil acidity have been reported by Fageria et al. (1995) in an Oxisol of Central Brazil.

TABLE 3. Concentration of nutrients in the shoots of common bean and lowland rice under different pH treatments.

pH H_2O	P g kg^{-1}	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}	Zn mg kg^{-1}	Cu mg kg^{-1}	Mn mg kg^{-1}	Fe mg kg^{-1}	B mg kg^{-1}
					Common bean				
4.9	2.1	32	27	8.3	70	9	4333	327	33
5.9	1.8	34	30	4.6	26	5	107	107	19
6.4	1.4	28	25	3.4	15	5	40	93	20
6.7	1.4	25	24	3.3	14	4	40	107	17
7.0	1.1	29	20	2.6	13	4	30	83	14
Regression									
β_0	-0.24	-37.89	-111.46	53.02	725.09	49.45	73973.66	3648.99	175.12
β_1	1.15	25.84	50.43	-13.60	-207.61	-12.65	-22714.34	-1074.90	-43.18
β_2	-0.13	-2.38	-4.51	0.92	15.13	0.88	1738.8	81.05	2.91
R^2	0.75**	0.14ns	0.58**	0.94**	0.89**	0.81**	0.90**	0.67**	0.90**
n	15	15	15	15	15	15	15	15	15
					Lowland rice				
4.9	3.1	35	2.2	2.5	37	25	1433	213	11
5.9	2.9	42	4.6	2.8	36	29	833	243	17
6.4	2.7	32	4.8	2.8	29	33	757	240	10
6.7	2.8	37	4.7	2.7	30	36	767	263	10
7.0	2.6	38	4.7	2.7	27	41	663	250	11
Regression									
β_0	4.57	25.66	-39.94	-40.59	10.68	116.27	9502.81	-92.13	-97.45
β_1	-0.31	3.33	13.78	14.01	12.82	-36.59	-2547.65	92.44	38.36
β_2	-0.004	-0.25	-1.06	-1.08	-1.50	3.68	184.32	-6.13	-3.30
R^2	0.72**	0.05ns	0.88**	0.88**	0.67**	0.94**	0.89**	0.15ns	0.13ns
n	15	15	15	15	15	15	15	15	15

*,**,ns=Significant at the 5 and 1% probability levels and not significant, respectively; n=number of measurements.

TABLE 4. Concentration of nutrients in the shoots of wheat, corn and soybean under different pH treatments.

pH H_2O	P $g\ kg^{-1}$	K $g\ kg^{-1}$	Ca $g\ kg^{-1}$	Mg $g\ kg^{-1}$	Zn $mg\ kg^{-1}$	Cu $mg\ kg^{-1}$	Mn $mg\ kg^{-1}$	Fe $mg\ kg^{-1}$	B $mg\ kg^{-1}$
					Wheat				
4.9	3.1	33	5.7	3.3	51	9	633	153	8
5.9	4.0	44	7.7	2.9	27	10	53	100	7
6.4	3.9	37	8.2	2.5	21	11	47	97	8
6.7	3.7	41	8.6	2.4	22	11	43	97	10
7.0	3.6	42	9.0	2.4	20	10	37	100	10
Regression									
β_0	-16.33	-76.07	-16.35	7.33	421.09	1.53	10229.67	1117.74	57.48
β_1	6.59	35.91	6.54	-1.03	-117.69	2.18	-3129.09	-315.77	-18.31
β_2	-0.53	-2.74	-0.42	0.04	8.64	-0.12	239.52	24.36	1.66
R^2	0.47*	0.19ns	0.88**	0.86**	0.96**	0.24ns	0.97**	0.78**	0.62**
n	15	15	15	15	15	15	15	15	15
					Corn				
4.9	1.7	40	4.8	2.9	39	6	483	73	9
5.9	2.1	39	7.3	2.5	19	6	53	80	10
6.4	2.2	37	8.5	2.5	15	7	63	87	11
6.7	2.2	43	8.7	2.3	15	7	57	100	10
7.0	1.9	39	9.6	2.2	13	7	40	87	11
Regression									
β_0	-9.50	97.79	-10.72	3.47	338.18	0.52	7821.86	2.06	3.49
β_1	3.78	-20.03	3.75	0.05	-94.57	1.22	-2402.02	17.85	1.33
β_2	-0.31	1.69	-0.12	-3.38	6.89	-0.04	185.11	-0.70	-0.04
R^2	0.47*	0.02ns	0.91**	0.34ns	0.96**	0.33ns	0.98**	0.28ns	0.34ns
n	15	15	15	15	15	15	15	15	15

Soybean									
4.9	1.8	27	14.8	5.2	56	5	1120	73	20
5.9	1.4	25	18.7	4.4	20	4	60	67	16
6.4	1.3	18	17.3	3.9	18	3	43	80	11
6.7	1.3	22	17.7	3.7	19	4	60	70	11
7.0	1.5	23	11.2	3.1	17	3	30	87	12
Regression									
β_0	11.27	110.83	-18.67	4.44	649.37	17.54	18877.61	372.27	89.52
β_1	-3.16	-26.96	10.48	0.95	-193.03	-3.73	-5795.81	-107.06	-20.93
β_2	0.25	2.03	-0.73	-0.16	14.71	0.24	444.46	9.42	1.38
R^2	0.50*	0.32ns	0.55**	0.91**	0.97**	0.72**	0.98**	0.31	0.84**
n	15	15	15	15	15	15	15	15	15

*, **, ns=Significant at the 5 and 1% probability levels and not significant, respectively; n=number of measurements.

Nutrient Concentration

There was a significant ($P<0.01$) effect of soil pH on the concentrations of P, Ca, Mg, Zn, Cu, Mn, Fe, and B in the shoots of common bean plants. (Table 3). The concentrations of P, Mg, Zn, Cu, Mn, Fe, and B decreased as soil pH increased from 4.9 to 7.0. Calcium and K concentrations in the common bean shoots increased as pH increased from 4.9 to 5.9, and beyond this range decreased the concentration. Maximum dry weight of shoots of common bean was achieved at soil pH 5.9 and the concentration of nutrients in the shoot at this pH may be considered at an adequate level. At this pH, the concentrations of nutrients were: P 1.8 g kg^{-1}, K 34 g kg^{-1}, Ca 30 g kg^{-1}, Mg 4.6 g kg^{-1}, Zn 26 mg kg^{-1}, Cu 5 mg kg^{-1} Mn 107 mg kg^{-1}, Fe 107 mg kg^{-1}, and B 19 mg kg^{-1} of dry plant tissue. Adequate levels of these nutrients reported by Fageria et al. (1997) for bean plants at the early growth stage fall within this range. Manganese concentration (4,333 mg kg^{-1}) was very high at the lowest soil pH (4.9), may be toxic for this crop, and it may be responsible for lower yield at lower pH. A Mn concentration of more than 500 mg kg^{-1} is considered toxic for common bean (Jones, 1972). At the highest pH level, concentrations of P (1.1 g kg^{-1}), Zn (13 mg kg^{-1}), Cu (4 mg kg^{-1}), and Mn (30 mg kg^{-1}), were lower than adequate levels of these nutrients reported by Fageria et al. (1997) for bean in the early growth stage (V_2-V_3), so at higher pH levels, deficiencies of these nutrients may be responsible for reduced growth.

The concentrations of P, Ca, Mg, Zn, Cu, and Mn in lowland rice were significantly influenced by soil pH (Table 3). The concentrations of Ca, Cu, and Fe increased quadratically and P, Zn, and Mn decreased with increasing soil pH. Maximum DMY was achieved at the lowest pH (4.9) level. At lower pH (4.9), Mn was accumulated relatively in higher concentrations (1,433 mg kg^{-1}). This suggests rice is tolerant to Mn toxicity. Tolerance of this crop to soil acidity is well known (Fageria et al., 1995).

The concentrations of P, Ca, Mg, Zn, Mn, Fe, and B in wheat plant shoots were significantly affected by soil pH treatments (Table 4). The concentrations of P and Ca increased quadratically, whereas Mg, Zn, Mn, and Fe decreased with increasing soil pH. At the lowest pH (4.9), Mn concentration in wheat tissue was 633 mg kg^{-1}, considered toxic for this crop (Jones, 1972).

The concentrations of P, Ca, Zn, and Mn in corn were significantly affected by soil pH treatments (Table 4). Phosphorus and Ca concentrations were significantly increased, whereas Zn and Mn concentrations were significantly decreased with increasing soil pH. At lower pH, concentration of Mn (483 mg kg^{-1}) is lower than the critical toxic level, which is reported to be about 500 mg kg^{-1} for annual crops (Jones, 1972). This indicates that corn is a Mn excluder and tolerant to soil acidity. At higher soil pH (>6), the decrease in crop yield may be related to deficiencies of Zn, Cu, and B. The concentrations of these nutrients at highest pH 7.0 are Zn (13 mg kg^{-1}), Cu (7 mg kg^{-1}), and B (11 mg kg^{-1}). These levels are lower than the critical levels reported in the literature for crop plants in the early growth stage. The critical Zn level is reported to be 30 mg kg^{-1}, Cu 15 mg kg^{-1}, and B 12 mg kg^{-1} in the early crop growth stage (Fageria et al., 1997).

The concentrations of P, Ca, Mg, Zn, Cu, Mn, and B in soybean were significantly affected by soil pH levels (Table 4). Phosphorus, Mg, Zn, Cu, Mn, and B concentrations were significantly decreased with increasing soil pH, whereas, concentration of Ca was increased quadratically with increasing soil pH. At the lowest pH (4.9), Mn concentration was quite high (1,120 mg kg^{-1}). This level may be toxic for this crop. Manganese concentrations of more than 600 mg kg^{-1} is toxic for soybean plants in a humid tropical soil (Fox et al., 1985). At higher soil pH, a decrease in yield of soybean may be related to a decrease in availability of Zn, Cu, Mn, Fe, and B. At higher pH (>6), Mn deficiency has been reported in the Oxisol of Brazil (Raij, 1991).

CONCLUSIONS

Increasing the soil pH from 4.9 to 6 provided an environment more conducive to shoots growth of wheat, soybean, and common bean, however, increasing pH did not have an effect on corn shoots growth and had a negative effect on rice growth. Rice DMY of shoots showed quadratic decrease with increasing soil pH. The tolerance of the tested crops to soil acidity can be defined in the order of lowland rice>corn>soybean>common bean>wheat. Increasing yield with increasing soil pH of the Inceptisol was associated with decreasing toxicity of Mn and improved Ca nutrition in the case of common bean, soybean, corn, and wheat crops. In general, at higher pH (>6), decrease in uptake of micronutrients might be responsible for decreased yield of crop species tested.

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